Clin Orthop Relat Res (2019) 477:1007-1018
DOI 10.1097/CORR.0000000000000576

Clinical Orthopaedics and Related Research®
A Publication of The Association of Bone and Joint Surgeons®

2018 Bernese Hip Symposium

Elite Rowers Demonstrate Consistent Patterns of Hip Cartilage Damage Compared With Matched Controls: A T2* Mapping Study

Bernd Bittersohl MD, Chiara Benedikter, Alexander Franz BSc, Tobias Hesper MD, Christoph Schleich MD, Gerald Antoch MD, Harish S. Hosalkar MD, FACS, FAAOS, Rüdiger Krauspe MD, Christoph Zilkens MD

Received: 13 May 2018 / Accepted: 30 October 2018 / Published online: 27 November 2018

Abstract

Background Rowing exposes the femoral head and acetabulum to high levels of repetitive abutment motion and axial loading that may put elite athletes at an increased risk for developing early hip osteoarthritis.

Questions/purposes Do elite rowers demonstrate characteristic hip cartilage lesions on T2* MRI sequences compared with asymptomatic individuals who do not row?

Methods This study included 20 asymptomatic rowers (mean age, 23 ± 3 years; nine females, 11 males) who had a minimum of 5 years of intensive (≥ 12 hours/week) training. The recruiting of the rowers took place from the central German federal rowing base, which has inherent intense training and selection requirements to declare these athletes as "elite rowers." We investigated one hip per study participant. MRI was performed on a 3-T scanner. The protocol included standard sequences, a double-echo steady-state sequence, and a multiecho data image combination sequence with inline T2* calculation (= the decay of transverse magnetization arising from molecular interactions [T2] and inhomogeneities in the magnetic field resulting from tissue susceptibility-induced field distortions and variations in the magnet itself), which detects changes in water content and the disruption of collagen structure. Although extrinsic and intrinsic influences on the T2* values including diurnal effects, MR technic-derived variations, and anatomic-related regional disparities need to be taken into account, low T2* values well below 20 ms indicate cartilage degeneration. Cartilage was morphologically analyzed in the anterior, anterosuperior, superoanterior, superior, superoposterior, posterosuperior, and posterior regions of the hip and graded as follows: Grade 0 = normal; Grade 1 = signal changes; Grade 2 = cartilage abrasion; Grade 3 = cartilage loss. Labrum was classified as follows: Grade 0 = normal; Grade 1 = partial tear; Grade 2 = full-thickness tear; Grade 3 = labrum degeneration. The T2* measurement was done through a region of interest

Clinical Orthopaedics and Related Research® neither advocates nor endorses the use of any treatment, drug, or device. Readers are encouraged to always seek additional information, including FDA approval status, of any drug or device before clinical use.
Each author certifies that his or her institution approved the human protocol for this investigation, that all investigations were conducted in conformity with ethical principles of research, and that informed consent for participation in the study was obtained. This study was performed at the University Hospital of Düsseldorf, Düsseldorf, Germany.

B. Bittersohl, C. Benedikter, A. Franz. T. Hesper, R. Krauspe, C. Zilkens, Department of Orthopedics, University of Düsseldorf, Medical Faculty, Düsseldorf, Germany

C. Schleich, G. Antoch, Department of Diagnostic and Interventional Radiology, University of Düsseldorf, Medical Faculty, Düsseldorf, Germany

H. S. Hosalkar, Hosalkar Institute, San Diego, CA, USA; Joint Preservation and Deformity Correction, Paradise Valley Hospital, San Diego, CA, USA; and Hip Preservation, Tricity Medical Center, San Diego, CA, USA

One of the authors certifies that he (RK) has received or may receive payments or benefits, during the study period, an amount of less than USD 10,000 from Corin (Cirencester, UK).

B. Bittersohl (✉), University of Düsseldorf, Medical Faculty, Department of Orthopedic Surgery, Moorenstr 5, 40225, Düsseldorf, Germany, email: bernd.bittersohl@med.uni-duesseldorf.de

All ICMJE Conflict of Interest Forms for authors and *Clinical Orthopaedics and Related Research*® editors and board members are on file with the publication and can be viewed on request.

Wolters Kluwer

analysis. For reliability assessment, morphologic evaluation and T2* measurement were performed by two observers while one observer repeated his analysis with a time interval > 2 weeks. Intra- and interobserver reliability was determined using κ analysis and intraclass correlation coefficients. Control T2* data were derived from a previous study on 15 hips in 15 asymptomatic volunteers of similar ages (seven males and eight females) who were not competitive rowers with similar MR hardware and imaging sequences.

Results Compared with the control group of asymptomatic volunteers who were not competitive rowers, we noted a high level of labrum and cartilage degeneration in the cohort of elite rowers. In the group of elite rowers, cartilage degeneration was noted in all hips. Regarding the acetabular cartilage, 271 zones could be evaluated. Of those, 44% (120 of 271) were graded normal, 6% (15 of 271) revealed signal alteration, 45% (122 of 271) demonstrated cartilage abrasion, and 5% (14 of 271) were noted to have full-thickness cartilage loss. Morphologic cartilage degeneration in the femoral head was less frequent. T2* values were lower than the control hips in all zones except for the posterior central acetabular zone (global T2* acetabular: 20 ± 6 ms, range, 9–36 ms, 95% confidence interval [CI], 19–21 ms versus 25 ± 5 ms, range, 14–44 ms, 95% CI, 24–25 ms, $p < 0.001$; global T2* femoral: 23 ± 7 ms, range, 9–38 ms, 95% CI, 22–24 ms versus 27 ± 5 ms, range, 17–45 ms, 95% CI, 26–28 ms, $p < 0.001$). The difference in T2* between the two study groups was superior in the peripheral zone of the anterosuperior region (16 ± 3 ms; range, 10–22 ms, 95% CI, 15–18 ms versus 26 ms ± 5 ms, range, 18–38 ms, 95% CI, 24–29 ms, $p < 0.001$).

Conclusions We found signs of hip cartilage degeneration to a much greater degree in elite rowers than in asymptomatic controls. Although causation cannot be inferred, this is concerning, and future investigations including controlled longitudinal studies both on elite and nonelite athletes with sufficient cohort size are warranted to clarify our findings.

Level of Evidence Level III, therapeutic study.

Introduction

Modern young athletes are pushing themselves harder and harder in competitive sports, sometimes at the cost of musculoskeletal injuries or increasing wear and tear. Different sports expose these athletes to different and perhaps unique patterns of joint or musculoskeletal injury. Much is known about hip injuries in sports like basketball, golf, ice hockey, and others [3]. Rowing is a common sport and known to cause its own set of musculoskeletal injuries, although hip involvement has not been specifically studied.

Rowing involves repeated cyclical axial loading with notable flexion, both motions capable of potentially causing hip cartilage or labral damage in the long run and possibly causing a unique characteristic pattern of damage. Radial or three-dimensional (3-D) cartilage-specific MRI sequences with high resolution to accurately assess the spatial morphology and joint structures such as the labrum and articular cartilage have proven to be reliable [7, 9, 12]. Biochemical-sensitive MRI techniques such as delayed gadolinium-enhanced MRI (dGEMRIC) [17], T2 mapping [15], T1rho imaging [11], chemical exchange saturation transfer imaging of glycosaminoglycan [13], and diffusion-weighted sequences [1] may be added to the protocol because they have the potential to detect early changes in the articular cartilage matrix. T2* mapping is a noncontrast MRI technique that is sensitive to water content and collagen anisotropy; it detects changes in water content and the disruption of collagen structure in cartilage damage and also allows for high-resolution isotropic 3-D imaging on standard clinical MRI systems [6].

We therefore sought to determine whether elite rowers demonstrate characteristic hip cartilage lesions on T2* MRI sequences compared with asymptomatic individuals who do not row. We hypothesized that there would be a pattern of cartilage degeneration involving the anterolateral region and axial loading comprising the superior region based on the specific demands on the hip in this sporting activity. We performed an observational, cross-sectional study in elite rowers with a descriptive and analytical assessment to prove our hypotheses.

Patients and Methods

The procedures in this study adhered to the ethical standards of the institutional review committee on human research. Each volunteer signed a written informed consent, and we obtained ethical approval from the local ethics committee.

Study Population

This study was performed on 20 selected elite rowers (nine females, 11 males; 15 sweep-oar rowers, five sculling rowers). Recruitment took place in the central German federal rowing base. After agreement of the trainers and the supervising physicians was obtained, the elite athletes from the under (U-)23 and senior level competing for Germany were asked for interest in the study. Of the 20 U-23 athletes and 32 senior (≥ 23 years old) athletes, 30 elite athletes volunteered. Of these, in turn, only asymptomatic (n = 26) participants were selected. Finally, nine female and 11 male subjects were selected to provide gender balance.

Seven of the women belong to the U-23 and two to the senior squad. Of the men, five compete for the U-23 team, whereas six male rowers compete for the senior team. The mean age was 23 ± 3 years. Age when high-level rowing began was 15 ± 2 years; the mean years of high-level rowing was 8 ± 3 years. All volunteers underwent a thorough physical examination conducted before MRI by an orthopaedic consultant with more than 5 years of experience in dedicated hip surgery. Briefly summarized, this included an investigation of pain, discomfort, tenderness, ROM, and the anterior femoroacetabular impingement test (groin pain provoked by hip flexion, internal rotation, and adduction). In the 20 rowers, 10 right and 10 left hips (one from each rower) were further investigated. The first five women and five men each had their right hip examined. In the remaining rowers, the left hip was scanned.

Foundation of T2 and T2*

Biochemical-sensitive MRI techniques such as T2 and T2* mapping have the potential to detect early changes in the articular cartilage matrix. Although there are similarities between T2 and T2*, the distinction between T2 and T2* relaxation is essential [6]. T2 is defined as a time constant for the decay of transverse magnetization (signal decrease caused by dephasing of the spins) arising from interactions between the spinning water atoms (spin-spin-relaxation). T2* refers to the loss of transverse magnetization arising both from spin-spin-relaxation and from local field inhomogeneities, which may be related to imperfections in the scanner magnets themselves and local magnetic susceptibility effects inside the patient. The typically lower spectrum of T2* values reflects the additional contribution of these coherent dephasing effects. In spin-echo techniques, 180° radiofrequency pulses are applied to cancel the local field inhomogeneities (not the interactions between the spinning water atoms) by reversing and rephasing the spins. T2* relaxation is noted only with gradient-echo imaging. Both T2 and T2* are sensitive to water content and the interaction between water molecules and collagen fibers in which a high T2 or T2* reflects high water content and superior water molecule mobility. This explains the decrease in T2 and T2* in deep cartilage zones where the vertically aligned collagen fiber orientation and high proteoglycan content are believed to cause water molecule restriction. The advantage of the spin-echo-based T2 mapping technique is the insensitivity to local field inhomogeneities (that may be substantial in the presence of postsurgery debris). Disadvantages include the long acquisition time that increases the risk for motion artifacts and prevents high-resolution isotropic 3-D MRI at tolerable measurement time. The T2* mapping technique has its advantages here because it offers fast imaging with the prospect of high image resolution, isotropic 3-D biochemically sensitive cartilage evaluation. These gains are of particular importance in the hip with thin, narrow, and spherically arranged cartilage surfaces.

The control T2* data for this study were derived from a previous study in which T2* relaxation measurements in the hip cartilage of asymptomatic volunteers were obtained in various age cohorts using similar MR hardware and imaging sequences [8]. To maximize the comparability of the study cohorts, we used the subgroup between the ages of 20 and 30 years. This group included 15 healthy individuals with no history of hip surgery and no hip complaints (eight females, seven males; mean age, 25.9 ± 2.3 years; seven right and eight left hips).

MRI

The MRI was performed on a 3-T machine (Magnetom Trio; Siemens Medical Solutions, Erlangen, Germany) with the volunteer in the supine position and a four-channel phased-array, flex surface coil placed around the hip being examined. The leg was stabilized with cushions and elastic straps to increase the comfort of the examination and to minimize movement artifacts.

The study MRI protocol included localizer images; standard pulse sequences with T1-, T2-, and PD-weighting in various planes; an isotropic high-resolution 3-D double-echo steady-state (DESS) sequence for morphologic cartilage assessment; and a 3-D gradient-echo high-resolution multiecho data image combination sequence with similar image resolution, six consecutive echoes, and inline T2* decay calculation according to a nonlinear least square fitting routine (Table 1).

Postprocessing and Cartilage Assessment

The 3-D volumes of the DESS and the T2* maps were processed on a Leonardo workstation (Siemens Medical Solutions). We used multiplanar reconstruction software to reformat seven 2-mm thick radial images around the femoral neck axis that depicted the anterior, anterosuperior, superoanterior, superior, superoposterior, posterosuperior, and posterior regions of the hip (Fig. 1). This postprocessing was done by an orthopaedic surgeon (BB) with > 11 years of experience in generating radial scans from a 3-D data set to depict the hip structures such as the labrum and articular cartilage in a perpendicular fashion with minimal distortion.

We analyzed acetabular and femoral cartilage as well as the labrum in these regions, whereas the acetabular and opposite femoral cartilage layers between the acetabular fossa and the chondrolabral junction were bisected into a peripheral and central zone.

Table 1. MRI protocol and imaging parameters utilized in this study

Imaging parameters	T1 TSE transverse	PD TSE FS transverse	STIR paracoronal	3-D DESS water excitation	3-D MEDIC T2* mapping
Repetition time (ms)	650	3400	5500	14.75	38
Echo time (ms)	9.5	11	32	5.03	4.62, 9.41, 15.28, 21.15, 27.02, 32.89
Flip angle (°)	130	150	120	25	25
Number of excitations	3	2	2	1	1
Field of view (mm^2)	200	180	260	192	192
Number of slices	33	40	20	176	144
Slice thickness (mm)	3	3.2	3	0.6	0.6
In-plane resolution (mm)	0.5 x 0.5	0.5 x 0.5	0.8 x 0.8	0.6 x 0.6	0.6 x 0.6
Bandwidth (Hz/pixel)	221	176	200	260	260
Acquisition time (minutes)	3:10	4:47	3:36	13:17	13:29

Partial Fourier acquisition (6/8 phase, 6/8 slice) combined with parallel imaging (GRAPPA, acceleration factor 2) was applied for the MEDIC sequence to achieve shorter imaging times; TSE = turbo spin echo; PD = proton density; FS = fat-saturated; STIR = short tau inversion recovery; 3-D = three-dimensional; DESS = double-echo steady-state; MEDIC = multiecho data image combination.

Cartilage status was graded as follows: Grade 0 = normal; Grade 1 = signal changes; Grade 2 = cartilage abrasion; or Grade 3 = cartilage loss. The labrum was classified as Grade 0 (normal, triangular-shaped); Grade 1 (partial tear); Grade 2 (full-thickness tear); or Grade 3 (degenerated, hypertrophied, and deformed labrum). In every instance, the worst possible grade was chosen if regions/zones revealed multiple features of cartilage or labrum degeneration. Cartilage and labrum assessment was performed by one orthopaedic surgeon (BB; reader 1) who is an expert in hip MRI with approximately 12 years of clinical experience in musculoskeletal radiology and one radiologist (GA; reader 2) who has 15 years of clinical experience in musculoskeletal radiology. Reader 1 repeated the grading with a time interval of at least 2 weeks to minimize recall effects. In every hip, the grading was performed independently. The T2* measurement was done through a region of interest (ROI) analysis where the ROI fields were placed in the four zones (peripheral acetabular cartilage, central acetabular cartilage, peripheral femoral head cartilage, and central femoral head cartilage) of each region using the corresponding DESS reformats as a guide to ensure that the ROI placement is within cartilage boundaries (Fig. 2). For the ROI placement, the DESS and corresponding T2* maps were loaded into a two-screen layout image area. DESS and the corresponding T2* image were displayed large enough with optimal image contrast and brightness to see details. Hip cartilage was then delineated on the DESS image using a freehand drawing tool. By selecting both images, the ROI drawn in the DESS image was automatically transferred to the T2* map, which reflects in some ways a copied and pasted approach. Afterward, the ROI outlines were reevaluated in the T2* map and, if necessary, only minimally shifted to correct for any ROI offset. The T2* measurement was done independently by one radiologist (CS; reader 1) and by one orthopaedic surgeon (CZ; reader 2) who had 6 years (reader 1) and 10 years (reader 2), respectively, of experience evaluating biochemical cartilage MRIs. Reader 1 repeated the T2* measurement with a sufficient time interval (minimum 2 weeks) between its first and its second analysis. Both T2* evaluators were blinded to the cartilage grades given by the other evaluators. Notably, T2* values well below 20 ms indicate cartilage degeneration [7]. A total of 560 cartilage zones (20 hips, seven regions, two zones per region, acetabular and femoral cartilage) and 140 labra (20 hips, seven regions) were assessed. In 19 zones, morphologic cartilage evaluation was abandoned. Either cartilage was absent in this zone (n = 13) or was not evaluable (n = 6) in a reliable fashion as a result of poor image quality. Therefore, 541 cartilage zones (97%) underwent morphologic grading. Two of 140 labra were not evaluable as a result of image quality issues, leaving 138 labra (99%) for further analysis. Kappa analysis was used to evaluate the intra- and interreader agreement on the cartilage and labrum grading scales. Intra- and interobserver agreement for the cartilage grading was high, revealing κ values ranging from 0.906 to 0.937 ($p < 0.001$). Intra- ($\kappa = 0.886$; $p < 0.001$) and interreader ($\kappa = 0.765$; $p < 0.001$) agreement for the labrum assessment was also high. T2* measurements could not be performed in a total of 72 cartilage zones because cartilage was absent (n = 13), inaccurate delineation of cartilage (n = 25) either as a result of poor tissue contrast or partial-volume effect related to insufficient in-plane resolution in this specific zone of the hip, imaging artifacts (n = 14),

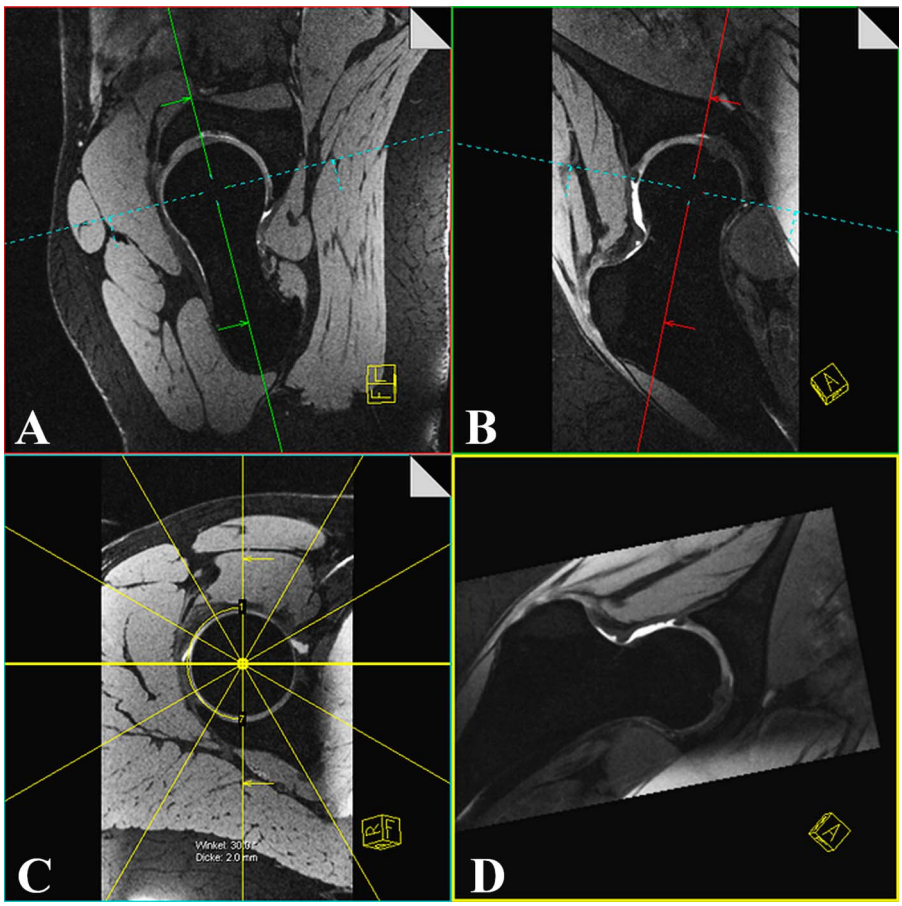

Fig. 1 A-D Multiplanar reconstruction (MPR) allows images to be created in any desired plane. (**A-B**) MPR was performed to generate a plane perpendicular to the femoral neck axis and (**C**) in the center of the femoral head. On this plane, radial reformats with an interval of 30° were generated. (**D**) This image depicts the superior region, which is the highlighted yellow line shown in C.

severe cartilage abrasion (n = 2), or cartilage loss (n = 18). Therefore, 488 T2* values (87%) underwent statistical assessment. Intraclass correlation coefficient (ICC) analysis with pairwise comparison and absolute agreement definition for reliability testing indicated high intra- and interreader agreement regarding the T2* measurement in acetabular (ICC, 0.906 and 0.915; $p < 0.001$) and femoral head (ICC, 0.937 and 0.927; $p < 0.001$) cartilage.

Statistical Analysis

The collected data were entered in an Excel spreadsheet (Version 14, Microsoft Office Professional; Microsoft Corp, Redmond, WA, USA) and later transferred to SPSS software (Version 25; IBM Corp, Armonk, NY, USA) by a biostatistician (SU) who conducted the statistical analysis in this study. The statistical analysis comprised descriptive data including mean values ± SD, range, 95% confidence intervals (CIs), and statistical tests such as κ analysis to evaluate the intra- and interreader agreement on ordinal (cartilage and labrum grading) scales and an ICC analysis with pairwise comparison and absolute agreement definition for reliability testing of quantitative measurements (T2* assessment). For the evaluation of regional differences on the T2* measurements and for group comparison (rower versus control cohort), a univariate analysis of variance with Bonferroni adjustment for multiple comparisons was conducted. Regarding the comparison with the control group, the mean values of the corresponding hip region were used as baseline values to compensate for regional differences in the T2* values possibly resulting from the magic angle effect [16], which promotes an increase in T2/T2* relaxation when collagen fibers are oriented 54.7° to the main magnetic field and possible regional differences in collagen density, fiber orientation, and water content. Probability values < 0.05 were considered to be statistically significant.

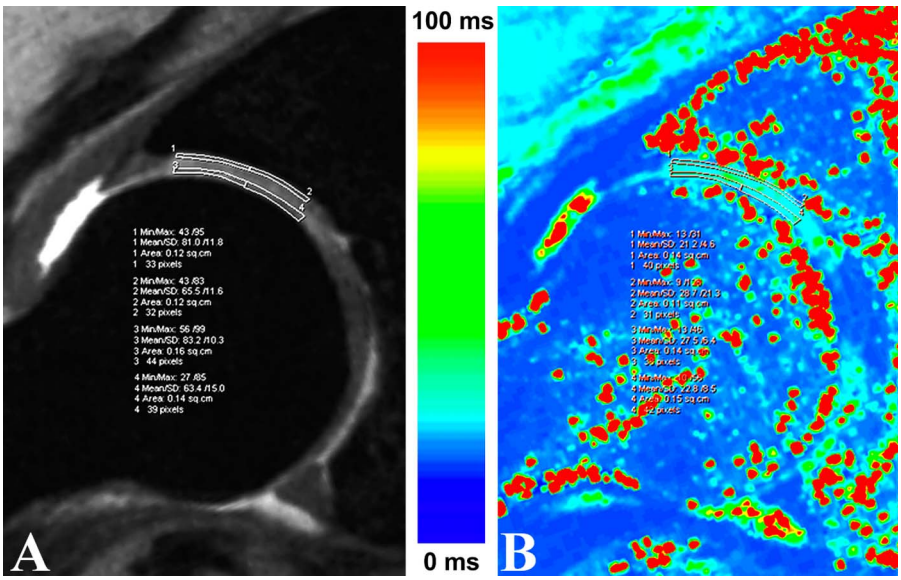

Fig. 2 A-B ROI analysis in central and peripheral acetabular and femoral head cartilage is shown. (**A**) The corresponding DESS image served as a guide to ensure ROI placement within cartilage boundaries. (**B**) T2* values are illustrated in a color scale whereby green reflects T2* values observed in healthy cartilage.

Results

Nineteen of 20 rowers' hips exhibited labral pathology. Of the 138 evaluated labral regions, 86 of 138 (62%) were graded normal, 23 of 138 (17%) were seen with a partial tear, three of 138 (2%) revealed a complete tear, and labrum degeneration was noted in 26 regions (approximately 19%). Therefore, 52 of 138 regions (approximately 38%) revealed some form of labrum damage.

We noted some grade of cartilage degeneration in all of the rowers' hips. Regarding the acetabular cartilage, 120 of 271 zones (44%) were graded normal, 15 zones (6%) revealed signal alteration, 122 zones (45%) demonstrated some degree of abrasion, and 14 zones (5%) were noted to have a full-thickness cartilage loss; this means that 56% of all cartilage zones revealed some degree of cartilage damage. With femoral head cartilage, morphologic cartilage degeneration was less frequent; 193 of 270 zones (72%) had normal-appearing cartilage, nine zones (3%) had signal alteration, 67 zones (25%) demonstrated cartilage abrasion, and only one zone (0.4%) had cartilage loss.

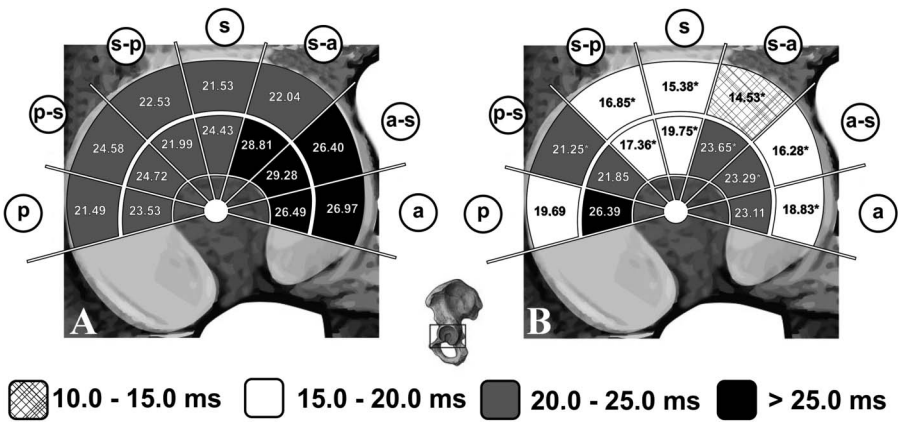

Fig. 3 A-B Regional and zonal distribution of mean T2* values in acetabular cartilage of healthy controls (**A**) and elite rowers (**B**) is shown. In the study cohort, lower T2* values were noted in almost all zones. A = anterior; A-S = anterosuperior; S-A = superoanterior; S = superior; S-P = superoposterior; P-S = posterosuperior; P = posterior. *$p < 0.05$.

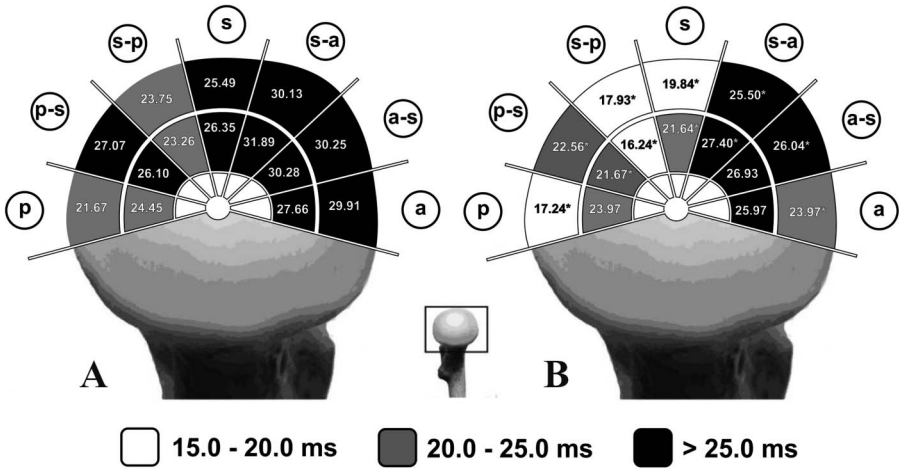

Fig. 4 A-B Regional and zonal distribution of mean T2* values in femoral head cartilage of healthy controls (**A**) and elite rowers (**B**) is shown. In the study cohort, lower T2* values were noted in all zones. A = anterior; A-S = anterosuperior; S-A = superoanterior; S = superior; S-P = superoposterior; P-S = posterosuperior; P = posterior. *p < 0.05.

The T2* values in acetabular (Fig. 3) and femoral head cartilage (Fig. 4) were lower than those in the control cohort. Differences were noted in 10 of 14 zones on the acetabulum (Table 2) and 11 of 14 zones on the femoral head (Table 3). The comparison between the peripheral and central zones revealed lower values in the acetabular peripheral zones in all regions except for the superoposterior and posterosuperior regions (Table 4). This pattern of lower cartilage T2* values in the peripheral zone was not noted in the femoral head except for the posterior region (Table 5). The acetabular T2* values in the posterior (23 ± 7 ms; range, 14–35 ms; 95% CI, 21–26 ms) and posterosuperior (22 ± 6 ms; range, 12–34 ms; 95% CI, 20–24 ms) regions were higher than those in the superior (18 ± 5 ms; range, 9–27 ms; 95% CI, 16–19 ms; p values, 0.002 and 0.030) and the superoposterior (17 ± 6 ms; range, 9–35 ms; 95% CI, 15–19 ms; p values, 0.001 and 0.009) regions. Within femoral head cartilage, we saw higher T2* values in the anterosuperior (27 ± 7 ms; range, 10–38 ms; 95% CI, 24–29 ms) and superoanterior (26 ± 6 ms; range, 12–37 ms; 95% CI, 25–28 ms) regions compared with the superior (21 ± 5 ms; range, 10–29 ms; 95% CI, 19–22 ms; p values < 0.001), superoposterior (17 ± 5 ms; range, 10–29 ms; 95% CI, 16–19 ms; p values < 0.001), posterosuperior (22 ± 6 ms; range, 9–34 ms; 95% CI, 20–24 ms; p values, 0.023 and 0.024), and posterior (21 ± 6 ms; range, 13–38 ms; 95% CI, 19–23 ms; p values < 0.001) regions. However, this pattern, albeit with overall higher T2* values, was also apparent in the control cohort.

Discussion

Damage to hip cartilage and labrum emanating from high levels of repetitive abutment flexion motion and axial loading can lead to a painful hip, restricted motion, and progressive cartilage damage that can occur in childhood and/or adulthood [2, 5]. The present study was performed to investigate whether a young cohort of elite rowers demonstrates a characteristic pattern of hip cartilage degeneration on standard and T2* MRI sequences compared with asymptomatic individuals who do not row. We noted a high level of labrum and cartilage degeneration, which was further underlined by significantly reduced T2* values in almost all joint regions. The T2* decrease was particularly prominent from anterior to superior in the peripheral zones (Fig. 5), probably reflecting the abutment at the acetabular rim during excessive flexion, and at the superior sector centrally and peripherally, consistent with progressive axial loading that likely begins as soon as the rower begins to apply power to the blade by pushing with their legs.

This study has limitations. Our study cohort included only athletes who were elite rowers. Therefore, our observations may not necessarily relate to recreational rowers. Further studies on nonelite athletes are needed to clarify whether this form of degeneration also occurs in recreational/nonelite rowers. The generalizability is further limited even for elite rowers because the numbers are still somewhat limited, leading to statistical power issues. Intraoperative validation was not available in our study and was a limitation. Nevertheless, reliability of cartilage and labrum assessment with the DESS and a T2* mapping technique has been confirmed in other studies [4, 7]. Although the cartilage was evaluated by morphologic grading and quantitative T2* relaxation time mapping, one of the limitations is comparison of the T2* values to a previously performed study on healthy volunteers likely because interfering variables that include changes in the MRI system over time cannot be entirely controlled. However, we

Table 2. T2* values in milliseconds in various regions and zones of acetabular cartilage in study and control groups*

Region	Zone	Cohort	Number	Mean	SD	95% CI	p value
Anterior	Peripheral	Rower	15	18.83	5.05	16.27-21.38	**< 0.001**
		Normal	15	26.97	7.22	23.31-30.62	
	Central	Rower	13	23.11	6.36	19.65-26.57	0.073
		Normal	14	26.49	4.93	23.91-29.08	
Anterosuperior	Peripheral	Rower	18	16.28	3.21	14.79-17.76	**< 0.001**
		Normal	15	26.40	5.45	23.64-29.16	
	Central	Rower	20	23.29	5.32	20.95-25.62	**< 0.001**
		Normal	15	29.28	5.02	26.74-31.82	
Superoanterior	Peripheral	Rower	16	14.53	3.50	12.81-16.24	**< 0.001**
		Normal	15	22.04	3.52	20.26-23.82	
	Central	Rower	19	23.65	4.87	21.46-25.84	**0.002**
		Normal	15	28.81	4.28	26.65-30.98	
Superior	Peripheral	Rower	18	15.38	4.03	13.52-17.25	**< 0.001**
		Normal	15	21.53	3.13	19.94-23.11	
	Central	Rower	18	19.75	4.62	17.62-21.88	**0.006**
		Normal	15	24.43	4.53	22.13-26.72	
Superoposterior	Peripheral	Rower	18	16.85	3.89	15.05-18.65	**0.001**
		Normal	15	22.53	4.27	20.36-24.69	
	Central	Rower	17	17.36	7.63	13.74-20.99	**0.008**
		Normal	15	21.99	2.84	20.55-23.43	
Posterosuperior	Peripheral	Rower	19	21.25	4.98	19.01-23.49	**0.049**
		Normal	15	24.58	2.65	23.24-25.92	
	Central	Rower	19	21.85	7.39	18.53-25.18	0.090
		Normal	15	24.72	4.69	22.35-27.09	
Posterior	Peripheral	Rower	12	19.69	5.50	16.58-22.80	0.344
		Normal	15	21.49	1.55	20.70-22.27	
	Central	Rower	14	26.39	6.23	23.13-29.66	0.116
		Normal	15	23.53	4.04	21.49-25.58	

*Significant differences were observed in many regions/zones (p values < 0.05 are highlighted in bold); CI = confidence interval.

believe that the data, in particular, the comparison of both cohorts, are reliable, because the MRI examination was performed on exactly the same MRI machine and with the identical sequence protocol. The patient and coil positionings were similar and were conducted by the same person (ER) who has been responsible for MRI measurements for several years. The data analysis was carried out using a model that has been tried and tested for many years by the authors. Of note, in asymptomatic hips, differences in age, the timing of the scan, and preimaging exercise did not show evidence of any inconsistency in the T2* values of hip cartilage. Given these circumstances and information, a high level of reproducibility can indeed be considered. When conducting a ROI analysis, one averaged value (in this case T2* value) per ROI will be obtained assuming that all voxels in this ROI reflect only cartilage tissue. However, the effects of partial (signal) volume averaging by mixing values of different tissues, for example superficial cartilage and synovial fluid or deep cartilage and subchondral bone, have to be taken into account, particularly when considering the thin and curved cartilage layers of the hip and the cubic voxel form. This limits the diagnostic accuracy and may potentially bias measurements, in particular when performing some form of quantitative assessment such as dGEMRIC, T2, and T2* mapping. Extensive research that includes high-resolution MRI and the generation of perpendicular planes has been undertaken to overcome this limitation. Although we appreciate this potential pitfall, our methodology is appropriate and therefore the results are valid. In our study, high isotropic resolution with an image resolution of 0.6 mm^3 was performed, which allowed us to create radial images with a slice thickness of 2 mm with sufficient signal-to-noise ratio and negligible image quality loss. The ROIs were outlined freehand by experienced investigators who did their best to measure cartilage tissue with a considerable amount of

Table 3. T2* values in milliseconds in various regions and zones of femoral head cartilage in study and control groups*

Region	Zone	Cohort	Number	Mean	SD	95% CI	p value
Anterior	Peripheral	Rower	18	23.97	5.92	21.24-26.71	**0.001**
		Normal	15	29.91	5.53	27.12-32.71	
	Central	Rower	13	25.97	5.69	22.88-29.06	0.406
		Normal	14	27.66	5.91	24.57-30.76	
Anterosuperior	Peripheral	Rower	19	26.04	7.26	22.78-29.31	**0.022**
		Normal	15	30.25	6.75	26.83-33.66	
	Central	Rower	19	26.93	7.66	23.48-30.37	0.067
		Normal	15	30.28	7.45	26.51-34.05	
Superoanterior	Peripheral	Rower	20	25.50	5.48	23.10-27.90	**0.011**
		Normal	15	30.13	3.42	28.40-31.86	
	Central	Rower	19	27.40	5.68	24.85-29.95	**0.014**
		Normal	15	31.89	4.79	29.47-34.32	
Superior	Peripheral	Rower	20	19.84	5.18	17.57-22.11	**0.002**
		Normal	15	25.49	4.03	23.46-27.53	
	Central	Rower	20	21.64	4.75	19.56-23.72	**0.010**
		Normal	15	26.35	3.80	24.42-28.27	
Superoposterior	Peripheral	Rower	20	17.93	4.27	16.06-19.80	**0.001**
		Normal	15	23.75	4.53	21.45-26.04	
	Central	Rower	18	16.24	4.99	13.94-18.55	**< 0.001**
		Normal	15	23.26	3.92	21.28-25.24	
Posterosuperior	Peripheral	Rower	20	22.56	5.47	20.16-24.95	**0.013**
		Normal	15	27.07	2.28	25.91-28.22	
	Central	Rower	18	21.67	6.59	18.63-24.72	**0.017**
		Normal	15	26.10	3.92	24.12-28.08	
Posterior	Peripheral	Rower	13	17.24	3.39	15.40-19.08	**0.028**
		Normal	15	21.67	1.78	20.77-22.57	
	Central	Rower	15	23.97	6.62	20.61-27.32	0.801
		Normal	15	24.45	3.54	22.66-26.24	

*Significant differences were observed in many regions/zones (p values < 0.05 are highlighted with bold); CI = confidence interval.

accuracy. Conversely, a few border pixels of potential cartilage tissue, which are also at risk of partial volume averaging, may not have been included within the ROI to ensure further that the data are not biased by partial volume averaging. This approach, however, reveals some risk for selection bias and variability in the outlining of the ROIs. A potential solution for this limitation is automatic cartilage segmentation by implementing some form of automatic surface and volume processing software. Notably, an increase in T2/T2* relaxation, when collagen fibers are oriented at an angle of nearly 55° (which is referred to as magic angle effect), needs to be taken into account [16]. This phenomenon might have contributed to the heterogeneity of the regional T2* distribution in this study (expected T2* increase in the anterosuperior and superoanterior as well as the posterosuperior and superoposterior regions, which are, depending on the pelvis and hip alignment during MRI, closest to the magic angle). However, in our study, this effect can be reproduced (only to some measure) both in the group of elite rowers and the control group. Furthermore, because this was an observational study, where the exposure to rowing started years before, we have no standardized activity protocol, which would include the daily activities of each rower. Also, in addition to the actual rowing, the sport comprises a variety of training techniques leading to different joint loading that we could not study. For that reason, a certain degree of inconsistency in the degeneration pattern must be considered. In sweep oar rowing, each rower has one oar held with both hands. Therefore, the rowers have to be paired so that there is an oar extending on each side of the boat. When the selection of which hip was further assessed, no specific consideration was given to whether the rowers favored the right or the left side. Therefore, side-dependent differences may have influenced the intraarticular findings. Finally, the participants included in our studies began rowing at a mean

Table 4. T2* values in milliseconds in peripheral and central zones in various regions of acetabular cartilage in elite rowers*

Region	Zone	Number	Mean	SD	95% CI	p value
Anterior	Peripheral	15	18.83	5.05	16.27-21.38	**0.034**
	Central	13	23.11	6.36	19.65-26.57	
Anterosuperior	Peripheral	18	16.28	3.21	14.79-17.76	**< 0.001**
	Central	20	23.29	5.32	20.95-25.62	
Superoanterior	Peripheral	16	14.53	3.50	12.81-16.24	**< 0.001**
	Central	19	23.65	4.87	21.46-25.84	
Superior	Peripheral	18	15.38	4.03	13.52-17.25	**0.014**
	Central	18	19.75	4.62	17.62-21.88	
Superoposterior	Peripheral	18	16.85	3.89	15.05-18.65	0.775
	Central	17	17.36	7.63	13.74-20.99	
Posterosuperior	Peripheral	19	21.25	4.98	19.01-23.49	0.726
	Central	19	21.85	7.39	18.53-25.18	
Posterior	Peripheral	12	19.69	5.50	16.58-22.80	**0.002**
	Central	14	26.39	6.23	23.13-29.66	

Lower T2 values were observed in the acetabular peripheral zones in all regions; all were statistically significant except for the superoposterior and the posterosuperior region (p values < 0.05 are highlighted with bold); CI = confidence interval.

age of 14.7 ± 2.4 years, which may already be too old for the development of a decided cam deformity through growth plate remodeling processes. Further prospective, randomized, blinded, controlled studies involving a study group that started rowing earlier may provide answers to this question.

In summary, we found characteristic hyaline cartilage lesions in the hips of our group of young elite rowers compared with nonrowers. These lesions were present on both the acetabular side and femoral head and were accompanied by characteristic labral defects as well. Our observations are similar to those of previous studies. Although Smoljanovic et al. [14] reported mostly minor hip injuries classically related to overuse in their cohort of junior competitive rowers (mean age 18 ± 1 years), a separate MRI-based examination of rowers with a symptomatic hip including femoroacetabular impingement (mean age 18.5 ± 0.6 years) revealed labral pathology in all participants, ranging from degenerative tearing to complex longitudinal tears [3]. Because many labral tears are associated with an earlier onset of articular cartilage degeneration and often originate with repetitive

Table 5. T2* values in milliseconds in peripheral and central zones in various regions of femoral head cartilage in elite rowers*

Region	Zone	Number	Mean	SD	95% CI	p value
Anterior	Peripheral	18	23.97	5.92	21.24-26.71	0.342
	Central	13	25.97	5.69	22.88-29.06	
Anterosuperior	Peripheral	19	26.04	7.26	22.78-29.31	0.637
	Central	19	26.93	7.66	23.48-30.37	
Superoanterior	Peripheral	20	25.50	5.48	23.10-27.90	0.305
	Central	19	27.40	5.68	24.85-29.95	
Superior	Peripheral	20	19.84	5.18	17.57-22.11	0.324
	Central	20	21.64	4.75	19.56-23.72	
Superoposterior	Peripheral	20	17.93	4.27	16.06-19.80	0.369
	Central	18	16.24	4.99	13.94-18.55	
Posterosuperior	Peripheral	20	22.56	5.47	20.16-24.95	0.638
	Central	18	21.67	6.59	18.63-24.72	
Posterior	Peripheral	13	17.24	3.39	15.40-19.08	**0.002**
	Central	15	23.97	6.62	20.61-27.32	

A pattern of lower cartilage T2 values in the peripheral zone was not noted in the femoral head except for the posterior region (p values < 0.05 are highlighted with bold); CI = confidence interval.

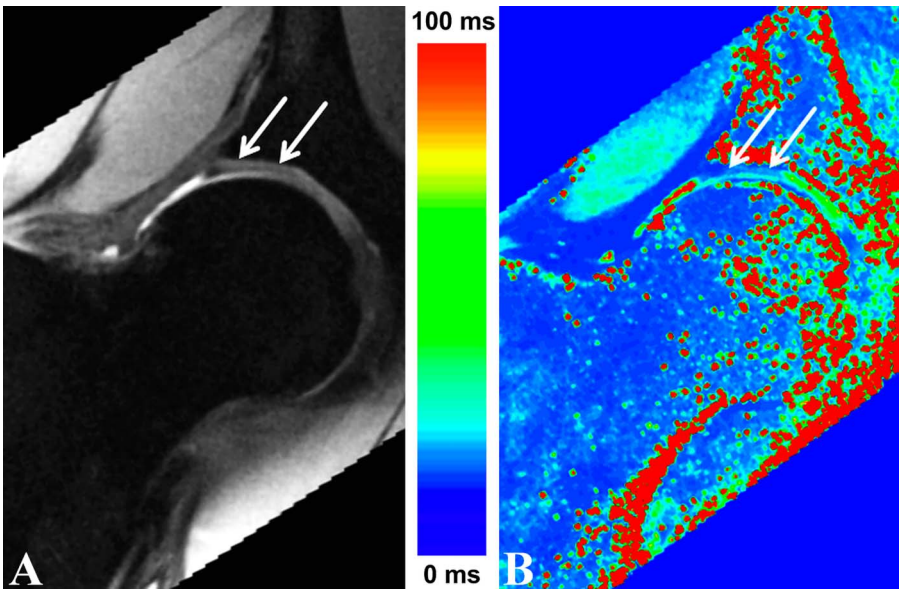

Fig. 5 A-B (**A**) DESS reformat, T2* color scale bar and (**B**) T2* map reformat of an asymptomatic rower are shown revealing mild cartilage thinning and a T2* decrease (white arrows in DESS image and T2* map) at the acetabular roof.

microtrauma [10], it may be assumed that our results are in agreement.

To understand abnormalities of hip morphology, and particularly, to correctly interpret the imaging findings, it must be understood that all quantifiable aspects are subject to a continuum, and there is a wide range of so-called normal sphericity of the femoral head or a normal extent of femoral head coverage or a reasonable ROM or a certain amount of joint loading within a given population. This also applies to the T2* mapping values. Thus, setting a certain threshold to define the normal or abnormal will always include outliers. In other words, these are numbers, not clinical symptoms. In fact, like with other diseases, we would not and should not base any diagnosis and any management therapy on a single number. Importantly, this study cohort included (still) asymptomatic individuals wherein morphologic and even MRI findings do not dictate or necessitate treatment. It is still unknown whether, and if so, in which time window the focal chondral defects necessarily progress to generalized joint degeneration and deterioration. Longitudinal, controlled and prospective studies, which should include a control group and various alternative therapies, should hopefully answer these questions.

Regarding the high amount of cartilage and labral damage noted in this study, and the low T2* values in pretty much all regions (which were more pronounced in the hip areas where the loading occurs), it is reasonable to conclude that extensive rowing in elite rowers may be a risk factor for early hip degeneration, including cartilage and labral damage, yet, although the morphologic and T2* changes were frequently observed in these hips, the data for a highly probable causation theory related to rowing are currently insufficient.

Acknowledgments We thank Mrs Erika Rädisch for helping perform the MRI, Dr Constantin Mayer who assisted with the clinical examination, and Mr Sebastian Ullrich, who conducted the statistical analysis in this study. Our sincere thanks also go to the study participants who have taken the time to participate despite tight training schedules.

References

1. Apprich S, Trattnig S, Welsch GH, Noebauer-Huhmann IM, Sokolowski M, Hirschfeld C, Stelzeneder D, Domayer S. Assessment of articular cartilage repair tissue after matrix-associated autologous chondrocyte transplantation or the microfracture technique in the ankle joint using diffusion-weighted imaging at 3 Tesla. *Osteoarthritis Cartilage*. 2012;20:703-711.
2. Beck M, Kalhor M, Leunig M, Ganz R. Hip morphology influences the pattern of damage to the acetabular cartilage: femoroacetabular impingement as a cause of early osteoarthritis of the hip. *J Bone Joint Surg Br*. 2005;87:1012-1018.
3. Boykin RE, McFeely ED, Ackerman KE, Yen YM, Nasreddine A, Kocher MS. Labral injuries of the hip in rowers. *Clin Orthop Relat Res*. 2013;471:2517-2522.
4. Ellermann J, Ziegler C, Nissi MJ, Goebel R, Hughes J, Benson M, Holmberg P, Morgan P. Acetabular cartilage assessment in patients with femoroacetabular impingement by using T2* mapping with arthroscopic verification. *Radiology*. 2014;271:512-523.
5. Ganz R, Leunig M, Leunig-Ganz K, Harris WH. The etiology of osteoarthritis of the hip: an integrated mechanical concept. *Clin Orthop Relat Res*. 2008;466:264-272.
6. Hesper T, Hosalkar HS, Bittersohl D, Welsch GH, Krauspe R, Zilkens C, Bittersohl B. T2* mapping for articular cartilage

assessment: principles, current applications, and future prospects. *Skeletal Radiol*. 2014;43:1429-1445.
7. Hesper T, Neugroda C, Schleich C, Antoch G, Hosalkar H, Krauspe R, Zilkens C, Bittersohl B. T2*-mapping of acetabular cartilage in patients with femoroacetabular impingement at 3 Tesla: comparative analysis with arthroscopic findings. *Cartilage*. 2018;9:118-126.
8. Hesper T, Schleich C, Buchwald A, Hosalkar HS, Antoch G, Krauspe R, Zilkens C, Bittersohl B. T2* mapping of the hip in asymptomatic volunteers with normal cartilage morphology: an analysis of regional and age-dependent distribution. *Cartilage*. 2018;9:30-37.
9. Knuesel PR, Pfirrmann CW, Noetzli HP, Dora C, Zanetti M, Hodler J, Kuehn B, Schmid MR. MR arthrography of the hip: diagnostic performance of a dedicated water-excitation 3D double-echo steady-state sequence to detect cartilage lesions. *AJR Am J Roentgenol*. 2004;183:1729-1735.
10. McCarthy JC, Noble PC, Schuck MR, Wright J, Lee J. The Otto E. Aufranc Award: The role of labral lesions to development of early degenerative hip disease. *Clin Orthop Relat Res*. 2001;393: 25-37.
11. Nemeth A, Di Marco L, Boutitie F, Sdika M, Grenier D, Rabilloud M, Beuf O, Pialat JB. Reproducibility of in vivo magnetic resonance imaging T1 rho and T2 relaxation time measurements of hip cartilage at 3.0T in healthy volunteers. *J Magn Reson Imaging*. 2018;47:1022-1033.
12. Pfirrmann CW, Duc SR, Zanetti M, Dora C, Hodler J. MR arthrography of acetabular cartilage delamination in femoroacetabular cam impingement. *Radiology*. 2008;249:236-241.
13. Schmitt B, Zbyn S, Stelzeneder D, Jellus V, Paul D, Lauer L, Bachert P, Trattnig S. Cartilage quality assessment by using glycosaminoglycan chemical exchange saturation transfer and (23)Na MR imaging at 7 T. *Radiology*. 2011;260:257-264.
14. Smoljanovic T, Bojanic I, Hannafin JA, Hren D, Delimar D, Pecina M. Traumatic and overuse injuries among international elite junior rowers. *Am J Sports Med*. 2009;37:1193-1199.
15. Watanabe A, Boesch C, Siebenrock K, Obata T, Anderson SE. T2 mapping of hip articular cartilage in healthy volunteers at 3T: a study of topographic variation. *J Magn Reson Imaging*. 2007; 26:165-171.
16. Xia Y. Magic-angle effect in magnetic resonance imaging of articular cartilage: a review. *Invest Radiol*. 2000;35:602-621.
17. Zilkens C, Miese F, Kim YJ, Hosalkar H, Antoch G, Krauspe R, Bittersohl B. Three-dimensional delayed gadolinium-enhanced magnetic resonance imaging of hip joint cartilage at 3T: a prospective controlled study. *Eur J Radiol*. 2012;81:3420-3425.